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Managing Aircraft Structural Safety Margins

Lessons Learned Derived From Helicopter and Fixed Wing Accident Reports

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Thesis: Fleet Management Paradigms

- **The Aviation Industry Operates to a Standard Mission**
  - Mission Profiles are not formally monitored or evaluated for impact on Operational Risk or Fleet Safety, long term
- **Visual Crack Detection Validates Airworthiness**
  - Airframe Fatigue Crack Detection Expectations are Incompatible with Helicopter Dynamic Systems Fatigue Life Management
- **Operators and Maintainers Manage Airworthiness**
  - No one fleet stakeholder maintains complete knowledge of various fleet Missions and their safety impact
    - Industry Stakeholders Include: Operators, Pilots, Maintenance, Original Equipment Manufacturers (OEM), and Regulatory agencies
  - Developing Mission Efficiencies is an adversarial business process

Accident Investigation Review
Fixed Wing Aircraft and Rotorcraft Reports

- **NTSB Aerial Fire Fighting:**
  Assessing Safety and Effectiveness
  - Harsh Mission Environment Dominates Mishap Causes
  - Fatigue of Primary Structure Caused Aircraft Mishaps

- **NASA Civil Rotorcraft Accident Report**
  –1963 through 1997 / Twin Turbine
  - Mechanical Failures Dominated Mishap Causes
  - Fatigue of Primary Dynamic System Structure is a Significant Cause of Rotorcraft Mishaps

Aerial Fire Fighting - Heavy Transport
NTSB Accident Causal Summary

- **Mission Loads**
  - 'The severity of the maneuver **loads** experienced by airplanes involved in firefighting operations' '**exceeded** both the maneuver **limit and ultimate** load **factors'**
- **Mission Spectrum**
  - 'These **repeated** and **high-magnitude maneuvers** and the repeated exposure to a turbulent environment **hasten the initiation of fatigue cracking** and **increase the growth rate** of cracking once it exists.'
- **Airworthiness**
  - '…**fatigue cracking** and **accelerated crack propagation can** and should **be addressed** through **maintenance programs**.'
- **Conclusion:**
  - '…**no effective mechanism** currently **exists to ensure the continuing airworthiness** of these firefighting aircraft.'

US Civil Rotorcraft - Twin Turbine Fleet
NASA Accident Causal Summary

- **Mission Spectrum**
  - ‘Past **design standards are inadequate relative to** the many **new and varied activities**’
- **Mission Loads**
  - ‘Pilots did **exceed design limits’**
- **Airworthiness**
  - ‘required and timely **maintenance was skipped’**
  - ‘…**less than thorough inspections** were performed,’
- **Conclusion:**

  ‘The **current fleet appears,** broadly speaking, to be **underdesigned in view of today's commercial usage’**

Accident Reports - Conclusions

- **Mission - Structural Characterizations**
  - Helicopter: **'Underdesigned'**
  - Firefighting: **'subjected to more severe operating environment than its original usage'**
- **Airworthiness - Process Weakness**
  - '**Inadequate maintenance** procedures **to detect fatigue cracking**'
- **Stakeholder Capability - Inadequate**
  - Operators '**did not possess engineering expertise**' 'to monitor' Mission load conditions and ' **predict** the effects of those stresses on the **operational life** of the airplanes'

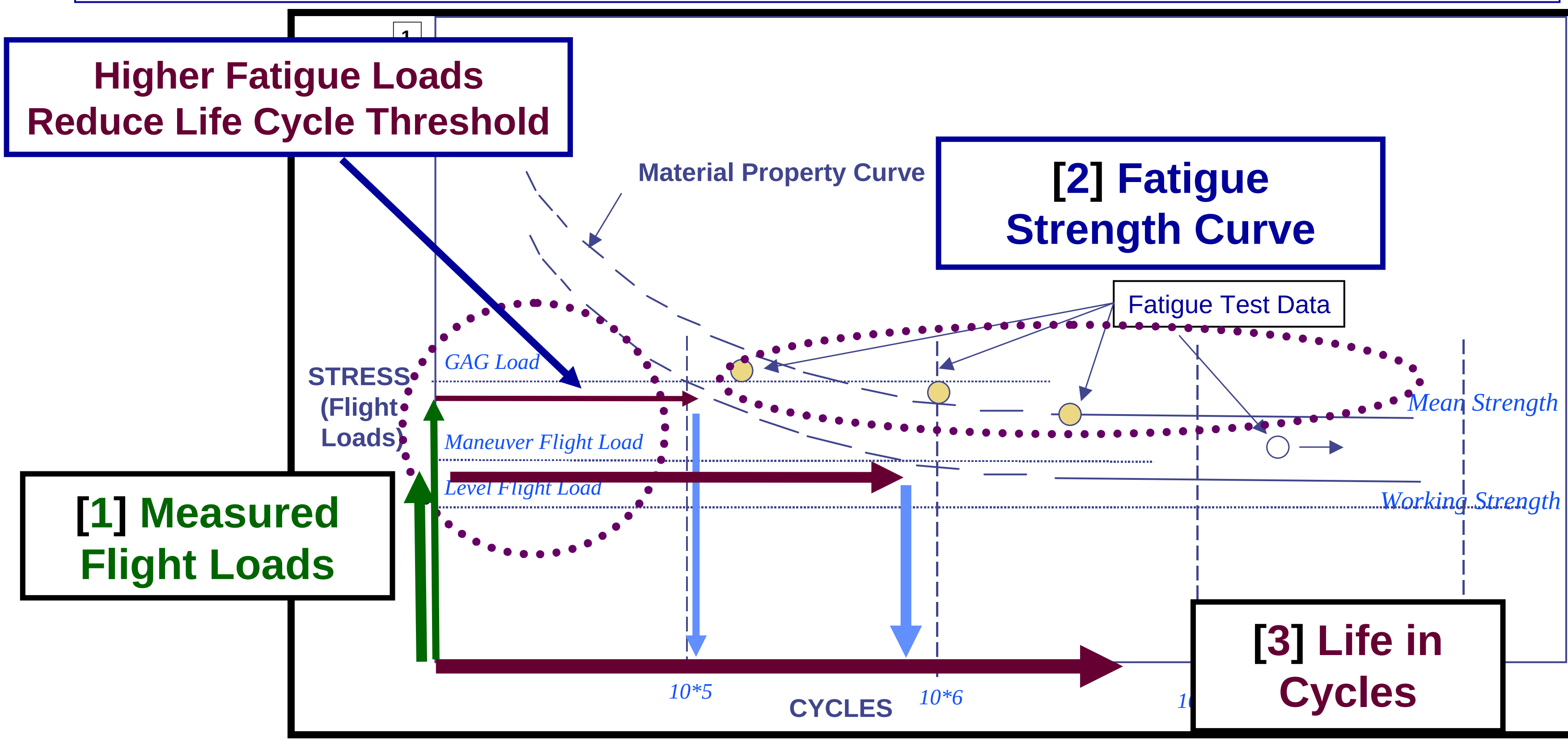
Implied Industry Paradigms
Derived From Report Conclusions

- **The Aviation Industry Operates to a Standard / Certified Mission**
  - Loading is Known and Repeatable
- **Aircraft Airworthiness Depends upon Crack Detection**
  - Inspection Intervals and Methods Reasonable
- **Operators and Maintainers Manage Fleet Airworthiness and Safety Risk**
  - Each Stakeholder is Capable of Evaluating Safety Risks of Varied Mission Conditions

Implied Industry Paradigms
Operating to a Standard Mission

<u>MINOR'S Cumulative Damage Theory</u>

1. **Measured Flight Loads**
   - [Projected Against]
2. **Material Strength of the Component**
   - [Establish Load Cycle Thresholds in:]
3. **Frequency and Duration for Individual Flight Loads**



Implied Industry Paradigms
Operating to a Standard Mission

- **Certified Mission Characteristics Include:**
  - **Load** Magnitude, **Spectrum** [Frequency of Load], Component **Strength**
- **Fatigue Sensitive Conditions Include:**
  - Dynamic or Static Loads that Exceed Design Limitations
  - Spectrum Operations that Exceed Certified Mission Spectrum Frequency
  - Environmental Conditions that Degrade Material Strength
- **Fatigue Margins of Safety**
  - OEM methodologies develop operational reliability of much better than 1 in 1,000,000 failure likelihood
    - Methods include: Structural Fatigue and Static Analysis, Subcomponent Tests, Full Scale Structural Testing, Full Scale System Flight Tests
- **Firefighting Mission Introduced a More Severe Fatigue Environment**
  - A Transport OEM Monitored and Evaluated the Fire Fighting Mission on Airframe Service Life
    - Results equal '5 to 7 times more severe than Passenger Service'
- **<u>Study Findings:</u>**

Operations that Alter Original Certified Mission Load, Spectrum, or Strength;

Reduce Structural Safety Margins and Increase Operational Risks, **long term**

Implied Industry Paradigm

Airworthiness - Maintenance Crack Detection

- **Standard <u>Airframe</u> Paradigm –**
  - Crack Development is Accepted in Multi-load path structure
  - Visual inspection is accepted as a Standard means to Determine Airworthiness
  - Inspection Procedures and Maintenance Intervals derive from Standard Mission Profiles
- **Standard <u>Helicopter</u> Dynamic System Paradigm**
  - No Cracks are permitted in Monolithic structure
  - Recommended Retirement Times (RRT) are the Standard Airworthiness Practice
  - Fatigue Calculations Derived from Standard Mission Profiles
- **<u>Study Findings:</u>**
  - the ‘Airframe Inspection Paradigm’ is <u>not</u> a practical or safe method to ensure Helicopter dynamic system Airworthiness

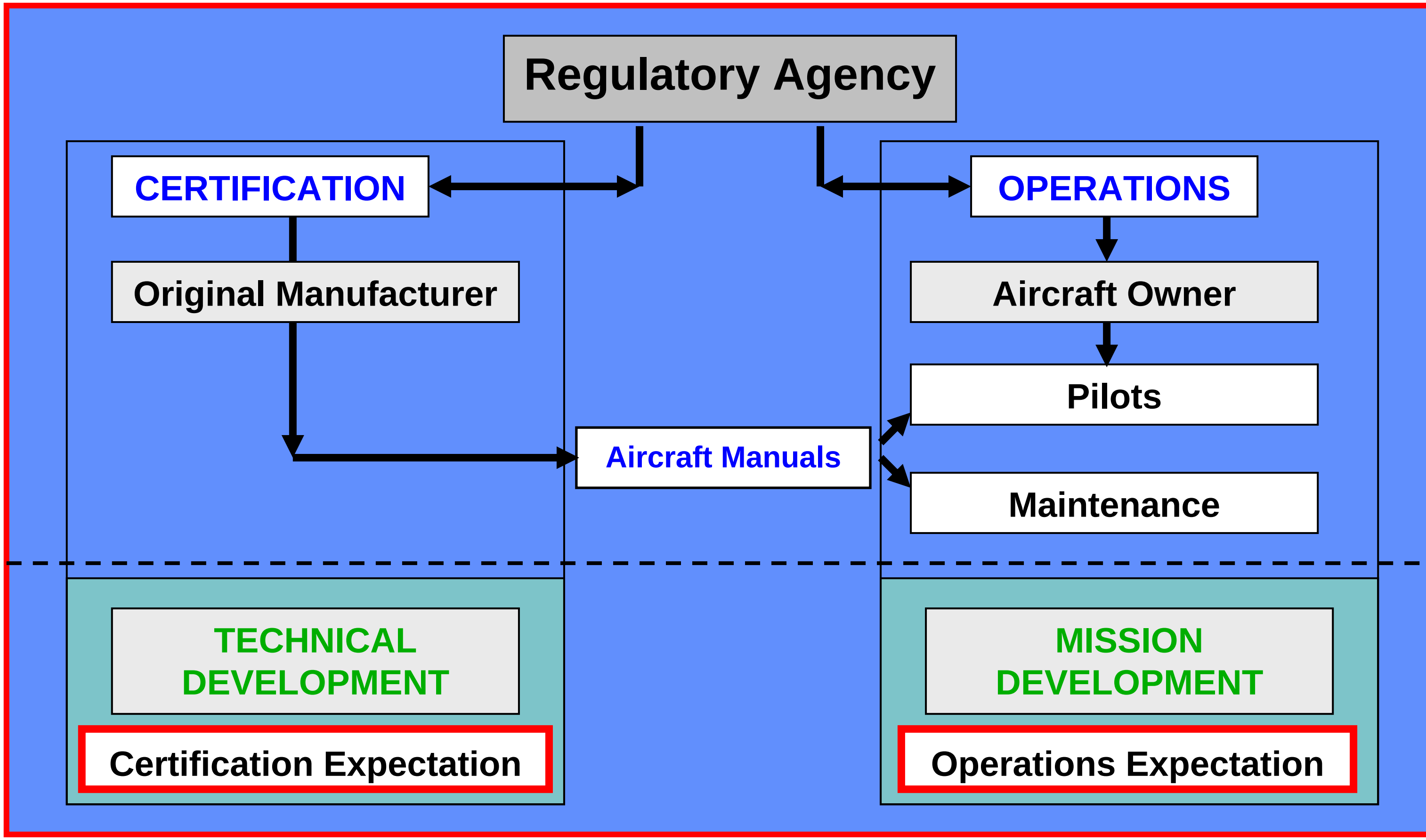
Implied Industry Paradigm
Managing Fleet Airworthiness / Safety Risk

- **Airworthiness Paradigm:**
  - Pilots Operate Aircraft Within Limits
  - OEM / FAA Certify Mission Spectrum
  - Owners Operate Within Mission Standards
  - Maintenance Follows Inspection Intervals For Standard Mission
  - Regulatory Agencies Verify Operations To Mission Standards
- **Then**: Safety Risks are Managed

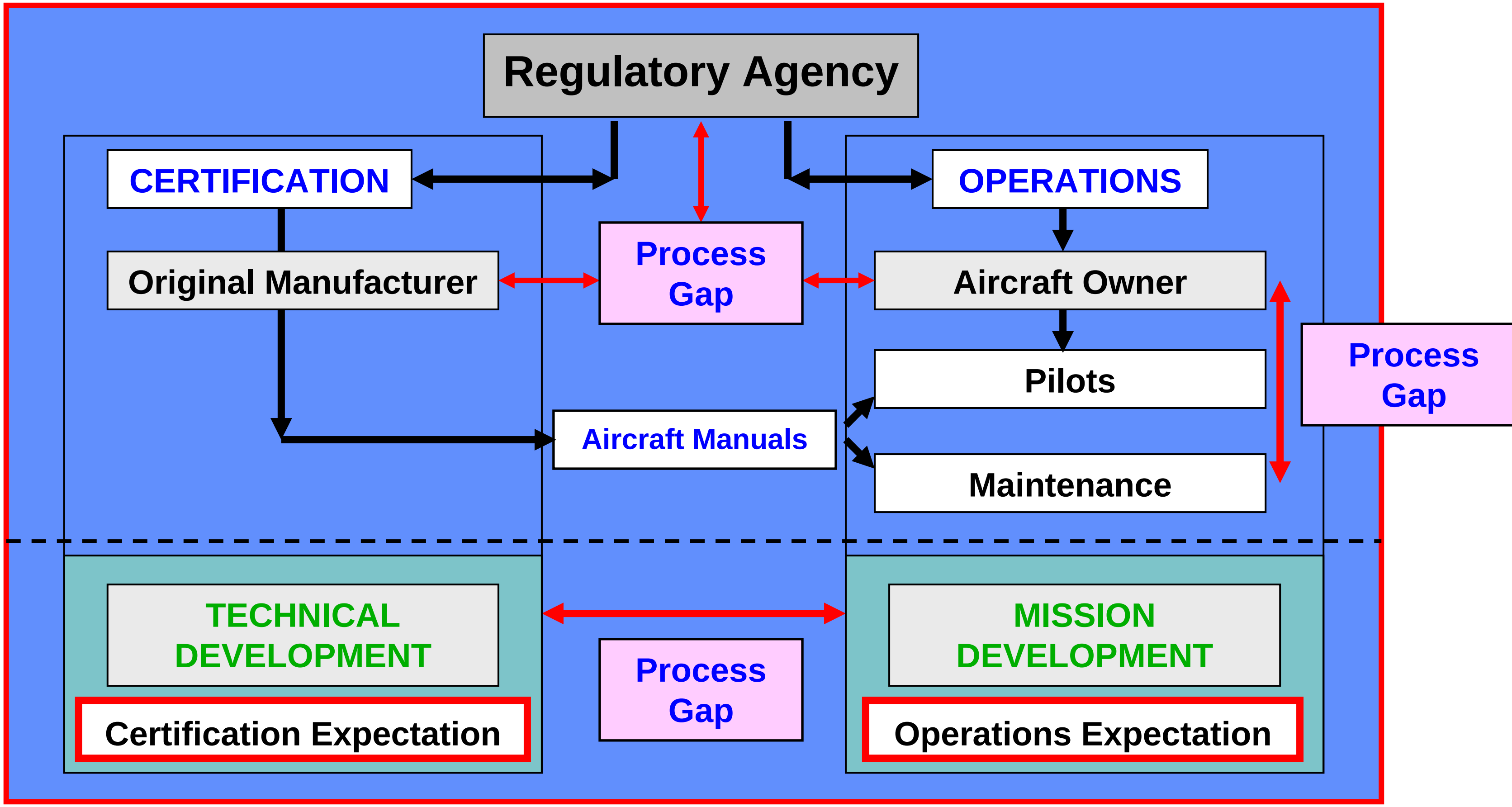
Implied Industry Paradigm
Managing Fleet Airworthiness / Safety Risk

- **Study Findings:**
  - Aircraft Conditions are ever changing due to Mission requirements
  - Potential Safety Process Gaps
    - Every Industry Stakeholder / Process Owner is Responsible to Manage a portion of the Safety Risk
    - Yet, No One Stakeholder is Fully Informed and Capable to Manage Every Airworthiness Issue and Safety Risk

Industry Processes and Expectations



Fundamental Process Gaps



Process Gap Conclusion

- **Conclusion:**
  - Stakeholders are not Fully Knowledgeable about Fundamental Safety Risks caused by Unique or Repeated Operations that Exceed Original Mission Design Parameters
- **However, This Does Not imply that Stakeholders are:**
  - Disinterested In Safety
  - Not Knowledgeable of Structural Issues
  - Or Unwilling to Eliminate Accident Causes

Closing the Process Gaps

- **Stakeholder Communication Limitations**
  - Certification or Mission Standards are not always followed.
  - Maintenance Inspection Procedures Not Directly Tied to Unique Mission Conditions
  - Some Operators not Able to Achieve Optimum Operational Safety due to Limited Technical Awareness of Mission Characteristics
  - Availability of Technical Information for Unique Missions is Limited
  - Piloting Awareness to Safely Operate Aircraft During Missions
- **Fundamental Understanding of Mission Operational Conditions is Lacking Within and Between the Helicopter Fleet Stakeholders**

Study Recommendations
Introduce Mission Based Management

- **Data Measurement Leads to Mission Awareness**
  - Safety Risks to Structural Margins Identified During Mission Development by Owner / Operators
- **Automated Measurement Systems are Available to Monitor Threshold and Load Exceedances**
  - Digital Engine Controls Function as Threshold Monitoring
- **Maintenance and Pilot Techniques May be Adjusted to Manage Fleet Airworthiness**
  - A Monitoring System Benefits Fleet Efficiencies
- **Measurement of Dynamic System Vibration and Temperatures for Shafting, Bearings, and Airframe**
  - Historically, 29 % of Helicopter Accidents are Structural

Published Accident Reports
Detail Data Summary

NASA Civil Rotorcraft Accident
Report –1963 through 1997 / Twin Turbine

- **Airplane Firefighting Mission Measurements**
  - Certified Limit and Ultimate **Loads** were Regularly Exceeded
  - An Airframe Manufacturer Analyzed a ‘5 to 7 Time’ **Usage** Acceleration during Firefighting

- **Civil Rotorcraft Accidents Distribution**
  - Dynamic System Mechanical Failure Rate
    - OF 302 Total Twin Turbine Accidents
      - (29%) 89 Dynamic System +(13%) 39 Engine
    - **Fatigue** is 42% of the ‘Cause’ Total
  - The Mishap Rate for the Tail Drive System is Equivalent to Single Turbine Accidents, on a percentage basis

Helicopter Accident Data
Civil Twin Turbine Helicopter

- **Mechanical Failures Represent 42% of Fleet Accidents**
  - (29%) 89 Dynamic System +(13%) 39 Engine

TABLE 31. TWIN-TURBINE ACCIDENT DISTRIBUTION, LAST 5 YEARS VS. 1963–1997

NTSB category	1992–1997		Last 34 years	
	Count	%	Count	%
Loss of engine power	14	10	39	13
In flight collision with object	19	13	43	14
Loss of control	21	15	40	13
Airframe/component/system failure or malfunction	39	27	89	29
Hard landing	3	2	8	3
In flight collision with terrain/water	11	8	16	5
Rollover/nose over	1	1	4	1
Other	35	25	63	21
Total	**143**	**100**	**302**	**100**

Helicopter Accident Data
Civil Twin Turbine Helicopter

- **Fatigue represents 37 % of Dynamic System Failures**

TABLE 34. NTSB FAILURE MODE/SYSTEM MATRIX—TWIN-TURBINE HELICOPTERS

Failure mode	Drive system	Rotor system	Control system	Airframe LG	Total
Fatigue	13	13	4	3	33
Improper assembly, installation, maintenance	3	1	7	3	14
Material failure	3	2	2	0	7
Undetermined/not reported	1	4	1	1	7
Failed	1	3	2	0	6
Separated	5	0	0	0	5
Foreign object damage	1	4	0	0	5
Overload	2	0	0	2	4
Pilot action/operational issue	1	1	0	1	3
Lack of lubrication	1	0	1	0	2
Total	32	29	18	10	89

Issue: 'The current fleet appears ...to be underdesigned in view of today's commercial usage.'